# Scientific report - 2014 - project IDEI-0153: 'ADVANCED STUDIES ON STRUCTURE AND DYNAMICS OF EXOTIC NUCLEI'

## I. ISOSPIN-SYMMETRY BREAKING AND SHAPE COEXISTENCE IN A∼70 ANALOGS

The interplay between isospin-symmetry-breaking and shape-coexistence effects in A∼70 analogs is self-consistently treated within the beyond-mean-field *complex* Excited Vampir variational model with symmetry projection before variation using an effective interaction obtained from a G-matrix based on the charge-dependent Bonn CD potential. Results are presented on Coulomb energy differences, mirror energy differences, triplet energy differences, and triplet displacement energy in the A=70 and A=74 isovector triplets.

Proton-rich nuclei in the A∼70 mass region are proper candidates to get insight into fundamental symmetries and interactions. In nuclei the isospin-symmetry breaking occurs due to the Coulomb interaction between protons and in the strong interaction due to the differences in the proton-proton, neutron-neutron and neutron-proton interaction strengths because of the mass difference between the up and down quarks and electromagnetic interactions among quarks. The charge-symmetry and charge-independence breaking could be investigated studying different isospin-related phenomena like Coulomb energy differences (CED), mirror energy differences (MED), triplet energy differences (TED), triplet displacement energy (TDE) among the triplet T=1 nuclei. Anomalies in the Coulomb energy differences have been identified in the A∼70 mass region for nuclei supposed to manifest shape mixing at low spins.

The investigation of the structure and dynamics of exotic nuclei around the N=Z line in the $A \sim 70$ mass region is one of the most exciting challenges in low energy nuclear physics. These nuclei display some rather interesting nuclear structure effects generated by the interplay between shape coexistence and mixing, competing like-nucleon and neutron-proton T=1 and T=0 pairing correlations, and isospin-symmetry-breaking interactions.

In the present study we will examine the isospin-symmetry-breaking effects on Coulomb energy differences, mirror energy differences, triplet energy differences, and triplet displacement energy for the A=70 and A=74 isovector triplets using the beyond-mean-field *complex* Excited Vampir variational approach. Recent experimental advances made possible the investigation of exotic nuclear structure phenomena in proton-rich medium mass nuclei, but the members of the T=1 triplet with $Z-N$=2 in the A∼70 mass region could be very difficult populated. This is the case of the $^{70}$Kr and $^{74}$Sr nuclei, while properties of the other members of the corresponding isovector triplets, $^{70}$Br, $^{70}$Se and $^{74}$Rb, $^{74}$Kr have been extensively investigated. Recently results on the spectroscopy of $^{74}$Sr have been reported.

Effects of the isospin nonconserving forces on the structure of medium mass nuclei have been studied using different theoretical approaches and various effective interactions. Recent studies on effects of the isospin nonconserving interactions in the T=1 analog states in the A$\sim$70 mass region by performing modern shell-model calculations indicated that the experimental trends in MED and TED can be reproduced adding to the Coulomb interaction some phenomenological isospin nonconserving nuclear interactions (INC), but the modern charge-dependent forces cannot account for the phenomenological strengths of the INC force.

Investigations based on the variational approaches of the VAMPIR model family have been successfully performed for the description of a variety of nuclear structure phenomena in the A$\sim$70 mass region, not only in nuclei along the valley of $\beta$-stability, but also in some exotic nuclei close to the proton drip line. The *complex* Excited Vampir approach allows for a unified description of low- and high-spin states including in the projected mean fields neutron-proton correlations in both the T=1 and T=0 channels and general two-nucleon unnatural-parity correlations. The oblate-prolate coexistence and mixing, the variation of the deformation with mass number, increasing spin, as well as excitation energy have been compared with the available experimental information. Since the Vampir approaches enable the use of rather large model spaces and of general two-body interactions, *large-scale* nuclear structure studies going far beyond the abilities of the conventional shell-model configuration-mixing approach are possible. Our previous investigations on microscopic aspects of shape coexistence in N$\simeq$Z nuclei in this mass region indicated the presence of a strong competition between particular configurations based on large and small oblate and prolate quadrupole deformations in the intrinsic system. Furthermore, as expected, since in N$\simeq$Z nuclei neutrons and protons fill the same single particle orbits, the neutron-proton pairing correlations were found to play an important role.

For nuclei in the A$\sim$70 mass region we use a $^{40}$Ca core and include the $1p_{1/2}$, $1p_{3/2}$, $0f_{5/2}$, $0f_{7/2}$, $1d_{5/2}$ and $0g_{9/2}$ oscillator orbits for both protons and neutrons in the valence space. We start with an isospin symmetric basis and then introduce the Coulomb shifts for the proton single-particle levels resulting from the $^{40}$Ca core by performing spherically symmetric Hartree-Fock calculations using the Gogny-interaction D1S in a 21 major-shell basis.

The effective two-body interaction is constructed from a nuclear matter G-matrix based on the charge-dependent Bonn one-boson-exchange potential Bonn CD. In order to enhance the pairing correlations this G-matrix was modified by adding short-range (0.707 fm) Gaussians with strength of -35 MeV in the T=1 proton-proton and neutron-neutron channnel, -20 MeV in the neutron-proton T=1 channel, and -35 MeV in the neutron-proton T=0 channel. In addition, the isoscalar interaction was modified by monopole shifts of -500 keV for all T=0 matrix elements of the form $\langle 1p1d_{5/2}; IT = 0|\hat{G}|1p1d_{5/2}; IT = 0\rangle$, where 1p denotes either the $1p_{1/2}$ or the $1p_{3/2}$ orbit. For the matrix elements of the form $\langle 0g_{9/2}0f; IT = 0|\hat{G}|0g_{9/2}0f; IT = 0\rangle$, where 0f denotes either the $0f_{5/2}$ or the $0f_{7/2}$ orbitals, monopole shifts of -370 keV (for A=70) and -275 keV (for A=74) have been added. These monopole shifts have been introduced in our earlier calculations in order to influence the onset of deformation. Previous results indicated that the oblate-prolate coexistence and mixing at low spins sensitively depend on the strengths of the neutron-proton T=0 matrix elements involving nucleons occupying the $0f_{5/2}$ or $0f_{7/2}$ and $0g_{9/2}$ single particle orbits. The Hamiltonian includes the Coulomb interaction between the valence protons.

In this report we presented the first results on the effect of isospin mixing on CED, MED, TED, and TDE in the A=70 and A=74 isovector triplets calculating the $0^+$, $2^+$, $4^+$, and $6^+$ states in these nuclei in the frame of the *complex* Excited Vampir model using an effective interaction obtained for the A$\sim$70 mass region starting from the charge-dependent Bonn CD potential. For the first time we estimated the isospin-symmetry-breaking effects taking into account both the Coulomb interaction and the isospin-symmetry violation in the strong force as it is considered by the Bonn CD potential. In order to improve the estimation of the isospin-symmetry-breaking effects we could increase the dimension of the many-nucleon bases used to describe the investigated analog states in all members of the isovector triplets. Furthermore, the refining of the effective interaction appropriate for the mass region under consideration requires more experimental data sensitive to particular parts of the Hamiltonian which could be relevant for the shape mixing and consequently for isospin-mixing effects. Of course, precise experimental data are needed on the analog states in $^{70}$Kr and $^{74}$Sr to confirm our predictions on mirror energy differences, triplet energy differences and triplet displacement energy. Extended experimental information on characteristic properties of A$\sim$70 isovector triplets testing the interplay between shape coexistence and isospin-nonconserving forces effects could test the theoretical predictions.

## II. TWO-BODY CORRELATIONS RELEVANT FOR THE STRUCTURE AND DYNAMICS OF PROTON-RICH MEDIUM MASS NUCLEI

### *Coulomb Energy Differences* , *Mirror Energy Differences* and *Triplet Energy Differences* in the A=66 isovector triplet

The characteristic properties of the proton-rich nuclei in the A~70 mass region are not only relevant to nuclear structure, but are of high interest for high precision tests of the Standard Model and for the astrophysical scenarios concerning the rp-process path.

We studied shape coexistence effects on Coulomb Energy Differences (CED), Mirror Energy Differences (MED) and Triplet Energy Differences (TED) in the A=66 isovector triplet using *complex* Excited Vampir model, in a relatively large model space using a realistic effective interaction (starting from a nuclear matter G-matrix based on the Bonn A potential). We also studied the two-body correlations in T=0 and T=1 channel relevant for the competition between the superallowed Fermi and Gamow-Teller (GT) β decay in the A=66 isovector triplet.

In $^{66}$As the calculated oblate(prolate) component amounts to 16(84)%, 29(70%, 18(81)%, and 4(95)% for the lowest $0^+$, $2^+$, $4^+$, and $6^+$ states, respectively, whereas for $^{66}$Ge the oblate(prolate) component results to be 20(80%, 38(61)%, 32(66)%, and 9(91)% for the corresponding states. The structure of the first excited $0^+$ state in $^{66}$As and $^{66}$Ge is dominated by an almost spherical prolate deformed configuration in the intrinsic system, characteristic only for the $0^+$ states. The third $0^+$ state and the first excited $2^+$, $4^+$, and $6^+$ states are dominated by oblate deformed configurations.

The predominantly prolate analog states in the $^{66}$As and $^{66}$Ge pair of nuclei show smooth changes of the prolate-oblate mixing with increasing spin which is reflected in the small positive trend of the corresponding CED in good agreement with the available data.

Using the same effective Hamiltonian we calculated the lowest positive parity states up to spin $6^+$ in $^{66}$Se. The results indicate that the projected prolate-deformed configurations in the intrinsic system dominate (more than 85%) the structure of the yrast states for each investigated spin. In figure 1 we present the theoretical MED and TED for nuclei belonging to the A=66 isovector triplet obtained within the *complex* Excited Vampir model compared with available data including the recent results on $^{66}$Se. The theoretical results present the trend indicated by the experimental data. The remaining discrepancies in the absolute values could come partly from the missing isospin-nonconserving nuclear interactions and partly from the dimension of the Excited Vampir many-body bases which should be increased. Both issues will be addressed in a future investigation.

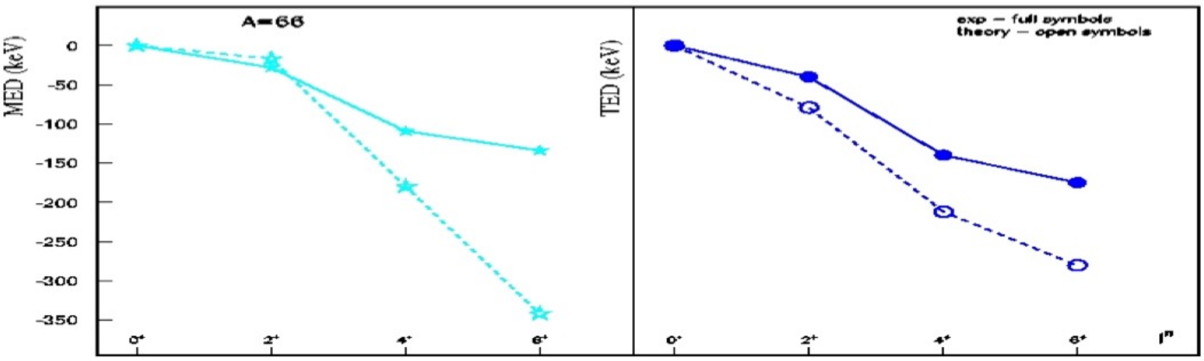


Fig.1. MED and TED for the A=66 isovector triplet

**Pairing correlations and Gamow-Teller β decay**

In medium mass nuclei near the N=Z line one expects a competition between like-nucleon and neutron-proton pairing correlations. In nuclear matter the isoscalar spin-triplet pairing interaction is stronger than the isovector spin-singlet pairing interaction. The isoscalar neutron-proton pairing correlations can give rise in the many-body nuclear systems to a new type of superfluidity, the neutron-proton pairing condensate, considered to be favoured in the N≈Z nuclei. An expected fingerprint for the superfluidity built on collective neutron-proton pairs should be the concentration of the Gamow-Teller (GT) β -strength for the decay of an even-even nucleus to the lowest T=0 $1^+$ state in the odd-odd N=Z daughter nucleus.

The analysis of the wave functions in terms of nucleon pairs coupled to particular quantum numbers gives valuable information on the structure of the various states. In particular the competition between the different pairing modes in proton-rich nuclei could be revealed by the pair structure of the many-body wave functions.

We define the pair number operator by:

$$\rho^{JTT_z\pi}_{(M)} \equiv \frac{1}{2}\sum_{n_il_ij_in_kl_kj_k}\delta\Big((-)^{l_i+l_k},\pi\Big)(-)^{j_i+j_k-M}(-)^{1-T_z}$$
$$\times\sum_{m_im_k\tau_i\tau_k}\langle j_im_ij_km_k|JM\rangle\langle\frac{1}{2}\tau_i\frac{1}{2}\tau_k|TT_z\rangle c^\dagger_{n_il_ij_im_i\tau_i}c^\dagger_{n_kl_kj_km_k\tau_k}$$
$$\times\sum_{m_rm_s}\langle j_k-m_rj_i-m_s|J-M\rangle\langle\frac{1}{2}-\tau_k\frac{1}{2}-\tau_i|T-T_z\rangle c_{n_kl_kj_km_r\tau_k}c_{n_il_ij_im_s\tau_i}$$

which can be considered as the trace of the scalar part of the two-body density. Its expectation values within a state with symmetry *s* count the number of nucleon pairs coupled to particular angular momentum, parity and isospin quantum numbers ($J^\pi$ ,T,$T_z$). Summing over J,π and T one obtains for each state the total number of nucleon-nucleon pairs in the considered nucleus A(A-1)/2 (since we use a core, A represents the total number of valence nucleons above the $^{40}$Ca core). Measuring the expectation values of this operator in percent of this total sum, trends in the pairing properties with changing nucleon number or increasing angular momentum and excitation energy can be analysed.

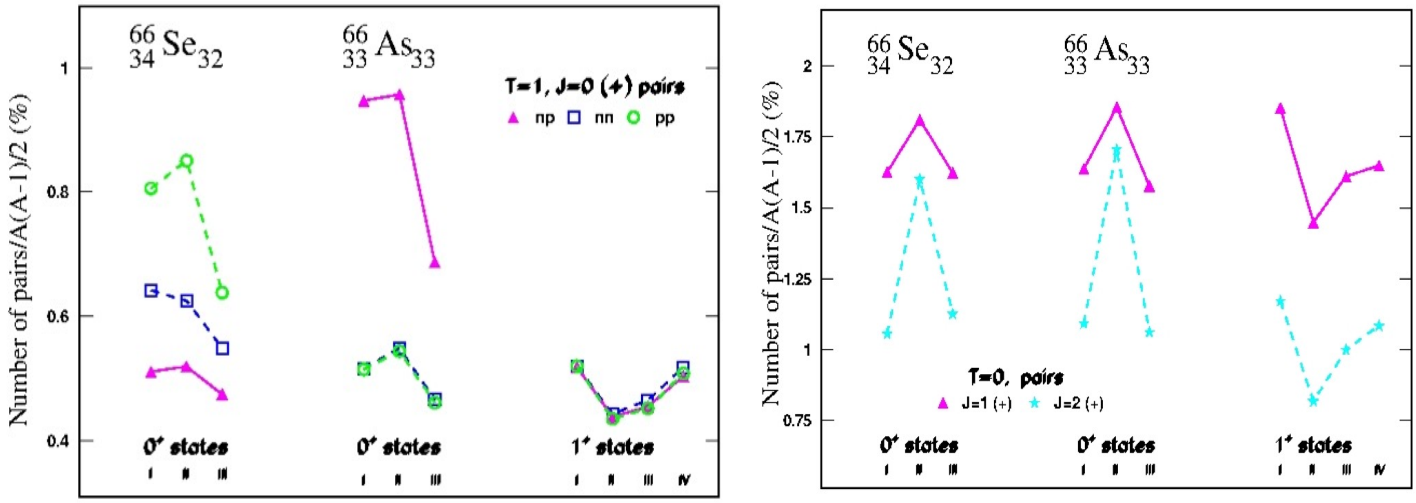


Fig. 2. The number of nn, pp, and np pairs with T=1, $J^{\pi}=0^{+}$ and the number of np pairs with T=0, $J^{\pi}=1^{+}$ and $J^{\pi}=2^{+}$ of the lowest $0^{+}$ in $^{66}$Se and the lowest $0^{+}$ and $1^{+}$ states in $^{66}$As in percent of the sum rule.

In the present work we shall present results on a pair structure analysis of $^{66}$Se and $^{66}$As, members of the A = 66. The motivation is connected with the possible competition of the superallowed Fermi and Gamow-Teller (GT) β decay of $^{66}$Se to $^{66}$As as a signature of the isoscalar proton-neutron pairing correlations. It is suggested that in medium mass nuclei an enhancement of the Gamow-Teller β decay of the ground state of an even-even Z = N + 2 nucleus to the lowest I = $1^{+}$ state in the daughter odd-odd N = Z nucleus would be expected as a fingerprint of the neutron-proton T = 0 condensate in the odd-odd system.

In $^{66}$As the EXVAM results for the lowest 4 $1^{+}$ states indicate that one oblate deformed configuration dominates the structure of the lowest state while the second, the third, and the fourth $1^{+}$ manifest mixing of differently deformed prolate configurations. In $^{66}$Se the oblate-prolate mixing in the structure of the lowest 3 $0^{+}$ states is comparable with the one found in the analog states in $^{66}$As varying strongly with the excitation energy. The EXVAM results indicate that the prolate components dominates the structure of the wave functions for the lowest 3 $0^{+}$ states in $^{66}$Se making a contribution of 85%, 97%, and 66%, respectively, to the total amplitude.

The calculated GT strength for the decay of the ground state of $^{66}$Se to the lowest $1^+$ state is negligible, while for the next excited states it amounts to 0.08 $g^2_A/4\pi$, 0.16 $g^2_A/4\pi$, and 0.37 $g^2_A/4\pi$, respectively.

In figure 2 we present the results for the pair structure analysis of the lowest 3 $0^+$ states in $^{66}$Se and the lowest 3 $0^+$ states and the lowest 4 $1^+$ states in $^{66}$As. Relevant for the absence of the proposed scenario concerning the neutron-proton pairing condensation in the N=Z odd-odd systems is the plot presented in figure 2 which indicates that the number of the neutron-proton pairs coupled to $J^\pi =1^+$, T=0 is maximum for the lowest $1^+$ state in $^{66}$As manifesting negligible Gamow-Teller strength.

We can conclude that we did not find an enhancement of the proton-neutron T=0 pairing correlations for the Gamow-Teller contributing low-lying $1^+$ states. We have to mention that from the experimental study performed at GSI-Darmstadt on the Gamow-Teller β decay of the $^{62}$Ge T = 1 $0^+$ ground state into excited states of the odd-odd N = Z $^{62}$Ga nucleus absence of the neutron-proton T = 0 condensate was inferred from the weak B(GT) observed.

## III. BEYOND-MEAN-FIELD DESCRIPTION OF THE GAMOW-TELLER BETA DECAY OF THE GROUND-STATE OF $^{72}$KR

The Gamow-Teller beta decay of the ground state of $^{72}$Kr is presented within *complex* Excited Vampir beyond-mean-field variational approach using an extended model space. The results are compared with the new experimental data obtained with TAGS (Total Absorption Gamma Spectrometer) at CERN- ISOLDE. The shape mixing is consistently described for both the $0^+$ ground-state of the even-even $^{72}$Kr nucleus and the $1^+$ states in the odd-odd $^{72}$Br.

The present study is the first atempt at a completely self-consistent calculation of Gamow-Teller beta decay of the ground state of $^{72}$Kr to $^{72}$Br using the complex Excited Vampir model in a very large model space involved in the description of A~100 nuclei. Our goal, in spite of the difficulties, is a comparison with the new experimental data obtained with TAGS spectrometer for an important waiting-point nucleus on the rp-process path, $^{72}$Kr.

We calculated the lowest eight $0^+$ states of the even-even parent nucleus $^{72}$Kr and the lowest 50 $1^+$ states in the odd-odd daughter nucleus $^{72}$Br.

In figure 1 we present the Gamow-Teller accumulated strengths for the decay of the ground state of $^{72}$Kr and compare them to the TAGS results. It is worthwhile to mention the we did not use quenching for the theoretical results. In the same figure we presented the theoretical results using an effective interaction obtained from a renormalised G-matrix based on BonnA/BonnCD potential in the originally used smaller model space

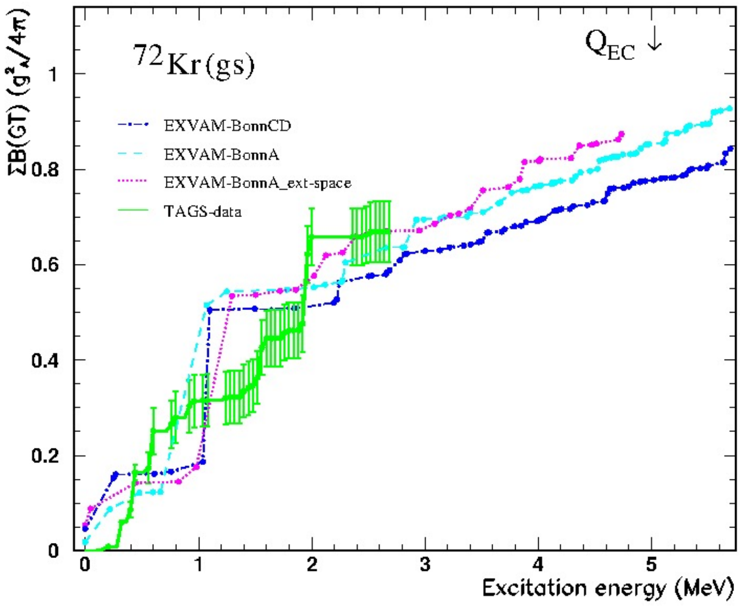


Fig.1. Gamow-Teller accumulated strengths for the decay of the ground state of $^{72}$Kr obtained within *complex* Excited Vampir model in two different model spaces using Bonn A/Bonn CD potential are compared with TAGS strength results.

The theoretical results on the Gamow-Teller strength distributions could be changed, at least for the high excitation energy region, by the higher-lying configurations nor included in the complex Excited Vampir many-nucleon basis. Also changes in the renormalisation of the effective interaction could influence the oblate-prolate mixing in the structure of the wav functions of both parents and daughter states.

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7. *Isospin−symmetry−breaking and shape−coexistence effects on structure and dynamics of medium mass nuclei,*

A.Petrovici (in collaboration with O. Andrei)**,** talk at *LIA Romania-France workshop*, Magurele, Romania, December 3-5, 2014

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